Are Electric Currents Heating the Magnetic Chromosphere?

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ABSTRACT

This paper presents an analysis of three-dimensional vector currents and temperatures observed in a sunspot from the photosphere to the chromosphere, spanning a range of heights of approximately 1500 km. With this unique dataset, based on novel spectro-polarimetric observations of the 850 nm spectral region, it is possible to conduct for the first time an empirical study of the relation between currents and chromospheric heating. It is shown that, while resistive current dissipation contributes to heat the sunspot chromosphere, it is not the dominant factor. The heating effect of current dissipation is more important in the penumbra of the sunspot, but even there it is still a relatively modest contribution.

Subject headings: line: profiles – Sun: atmosphere – Sun: magnetic fields – Sun: chromosphere

Currents are thought to play an important role for the energetics of the chromosphere and the corona of the Sun and, by extrapolation, of cool stars in general. Essentially, three types of processes have been proposed to explain the chromospheric heating problem (Ulmschneider et al. 1991): a)heating by upward-propagating waves (acoustic and/or magnetic, Carlsson & Stein 1992; Alfvén 1947); b)energy release by magnetic reconnection(Parker 1988) and c)resistive dissipation of electric currents (Rabin & Moore 1984; Goodman 2004). Unfortunately, the remote detection of solar electric currents is very challenging and requires accurate 3D vector magnetometry to solve, at each spatial point, the vector equation $\vec{j} = \nabla \times \vec{B}$. Because of this, the measurement of currents in the chromosphere has been essentially limited to the recent work of Solanki et al. (2003), based on the He I multiplet at

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1083 nm. These lines have the advantage that they can be analyzed with a simplified modeling technique and one does not need to deal with the complications of detailed non-LTE radiative transfer calculations. The drawback is that this simplified analysis does not allow the authors to obtain temperatures or even to determine empirically the height of measurement (which varies from pixel to pixel). While that work was an important step forward, it could not establish whether electric currents constitute an effective heating source.

The observations used in this work were acquired on June 2004 with the new instrument SPINOR (Spectro-Polarimeter for Infrared and Optical Regions, Socas-Navarro et al. 2005a). The dataset, consisting of a spectro-polarimetric scan of NOAA 0634 in the 849.8 and 854.2 nm spectral region, was analyzed with the non-LTE inversion code of Socas-Navarro et al. (2001). This produced a 3D reconstruction of the temperature, velocity and magnetic field vector from the photosphere to the chromosphere (a more detailed account is given in Socas-Navarro 2005).

Having the 3D structure of the vector magnetic field, one can compute the vector current density as the curl of the field. Figure 1 shows maps of the current density at different heights in the atmosphere. The strongest currents are organized in filamentary structures, at least when viewed in these 2D representations (horizontal cuts). In 3D their appearance is more reminiscent of "sheets". The western boundary of the sunspot (right of the images) exhibits a very prominent system of strong currents, especially in the photosphere. As I discuss below, these currents are not aligned with the vector field, which implies that the field is "forced" (i.e., non-force-free). The magnetic topology in the area surrounding the spot is very different on both sides of it, as evidenced by larger-field magnetograms (not shown in the figure). While the east side is almost devoid of strong flux, the west side harbors a very intricate pattern of strong magnetic fields. It is interesting to note that Hα images of this active region show considerable activity on the west side very near the sunspot. Moreover, we identified two Ellerman bombs (Socas-Navarro et al. 2005b) located off of the edge of the western penumbra. The combination of Hα emission, Ellerman bombs and complex field topology is a symptom of ongoing magnetic reconnection, which is consistent with the presence of strong currents such as those shown in the figure.

Figure 2 shows the angle between the currents and the magnetic field lines. In a force-free field this angle would be either 0 (parallel) or 180 (anti-parallel) degrees everywhere. We can see that, as one would expect, the field is more force-free in the chromosphere than in the photosphere. However, even the higher chromosphere is far from being entirely force-free. Only the inner part of the eastern penumbra is fairly force-free and exhibits a pattern of alternating parallel/anti-parallel field-aligned currents running along the penumbral filaments. The filamentary structure extends outwards, even beyond the limit of the visible penumbra,

but with significant inclinations with respect to the field lines. The same pattern of incoming/outgoing non-field-aligned currents is visible in the North-East (upper-left) quadrant of the photospheric penumbra.

The reliability of the results presented in Figs 1 and 2 is supported by several noteworthy arguments: The inversion code has been extensively tested (Socas-Navarro et al. 2001) and found to produce a good representation of the average thermal and magnetic conditions in the spatial pixel. The parameters reconstructed by the tomography (temperature, magnetic field, currents, etc) exhibit smooth pixel-to-pixel variations and spatial coherence, even though each pixel was inverted independently. Particularly interesting is the fact that currents appear as filaments in the maps (or sheets in 3D), which would be difficult to produce by artifacts of the analysis. Furthermore, the results obtained are physically sensible (the field is more force-free in the chromosphere than in the photosphere, the connection of strong currents with Hα emission and Ellerman bombs, the filamentary pattern extending even beyond the visible penumbra, etc). But perhaps the most convincing test for the accuracy of the tomography is that of the divergence of the field which, according to the Maxwell equations, should be zero everywhere. I have verified that this divergence, computed using boxes of 1.4 Mm side, is always small when compared to B/l (the ratio of the field strength over the length of the box), with an average absolute value of 1.8% of that ratio. Again, this would be very difficult to produce by random or systematic analysis errors.

The most important source of error in obtaining the currents is the z-scale, i.e. the geometrical height of each point in the 3D grid. We carried out a very thorough treatment of the height scale, including a correction of the Wilson depression by matching the total (gas and magnetic) pressure at neighboring points (Sánchez Almeida 2005). Still, uncertainties are to be expected of up to 50-100 km through the photosphere and 200-300 km in the chromosphere. A Montecarlo-type error analysis was conducted by adding random perturbations to the z-scale at each (x,y)-point and recomputing the vector current density. The maps obtained did not change significantly by perturbations at this level (with relative errors of $\sim$10%), which is a natural consequence of the field gradients being relatively smooth in the sunspot.

It is also important to consider the effects of unresolved structure in the observed pixel, since penumbral filaments are known to be organized on small scales. In such situations the inversion procedure retrieves an average of the thermal and magnetic conditions in the resolution element. By taking volume integrals on both sides of the equation above, and using the mathematical property that the integral of the curl is the curl of the integral, it is straightforward to see that one then obtains the average current in the resolution element.

Let us now turn to the thermal structure of the sunspot and its relation to electric

currents. Figure 3 shows horizontal cuts of the electron temperature at several heights. We can see that the chromosphere exhibits "hot patches", with typical size scales of $\sim$5 Mm, embedded in a cooler medium. When this figure is compared to the current density maps discussed above, we can see that they are fundamentally different and there is no obvious connection between chromospheric hot spots and the strong current sheets. A more quantitative analysis is presented in Fig 4, which shows the spatial correlation between currents and temperatures. Notice that, even though the overall correlations are very weak, they are nearly always positive. This is an indication that current dissipation is indeed contributing to the chromospheric heating above sunspots, but it is not the dominant mechanism. The correlation coefficient increases by about a factor of two (but still remains weak) if we restrict the analysis to the penumbral region (right panels), suggesting that the effect of electric currents is more important in the penumbra. It has been proposed (see e.g., Goodman 2004) that only the component perpendicular to the field (the so-called Pedersen currents) is relevant for the heating of the upper atmosphere. The correlation curves for the entire region (left panels in the figure) do not generally show a clear distinction between both components. However, the penumbra (right panels) exhibits a slightly better correlation with the Pedersen component, in agreement with that statement.

The results presented in this letter do not just argue against resistive current dissipation as a dominant source for chromospheric heating. Since magnetic reconnection is associated with strong current sheets, we can also conclude that reconnection must not be important, at least in the relatively simple magnetic topology of sunspots (the situation is likely to be different in more complex regions, such as the emerging flux scenario analyzed by Solanki et al. 2003). This leaves only one of the three types of mechanisms mentioned above, namely the dissipation of (acoustic or magnetic) waves. In a recent work, Fossum & Carlsson (2005) claim that acoustic waves do not carry enough energy to sustain the heating rate of the upper solar atmosphere. The combination of their results with the ones presented here appears to point directly to Alfvén waves as the dominant heating source, at least in sunspots.

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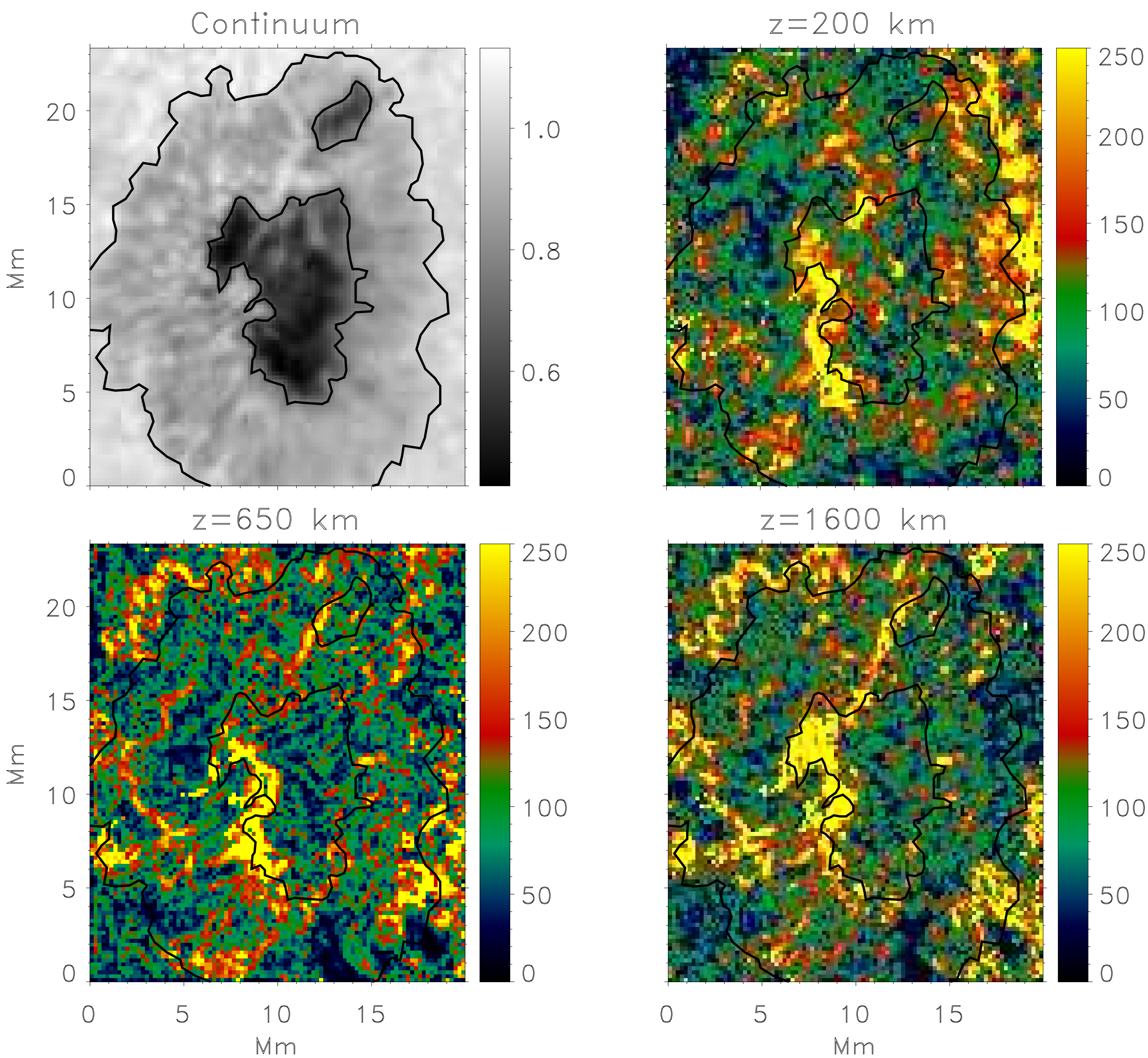

Fig. 1.— Upper left: Continuum image of the sunspot analyzed in this work (in units of the average quiet Sun). North is up and East is left of the image. The rest of the panels present current density maps (units are 10^3 A/km^2) at z=200, 650 and 1600 km. The z=0 level is the height at which the continuum optical depth at 500 nm reaches unity (τ_{500}=1) in the quiet Sun.

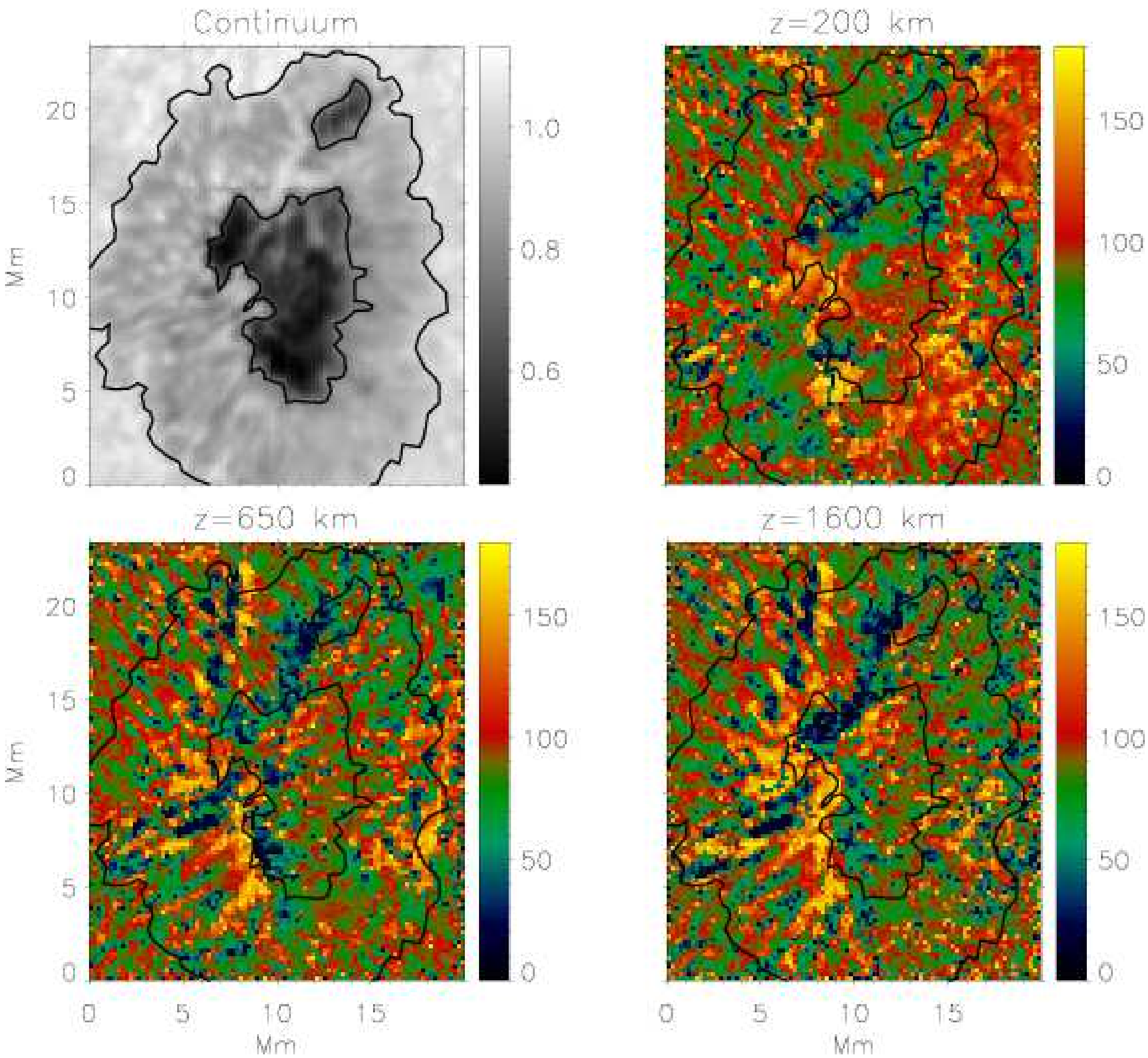

Fig. 2.— Upper left: Continuum image of the sunspot analyzed in this work (in units of the average quiet Sun). North is up and East is left of the image. The rest of the panels present the angles (degrees) between the vector current and the magnetic field.

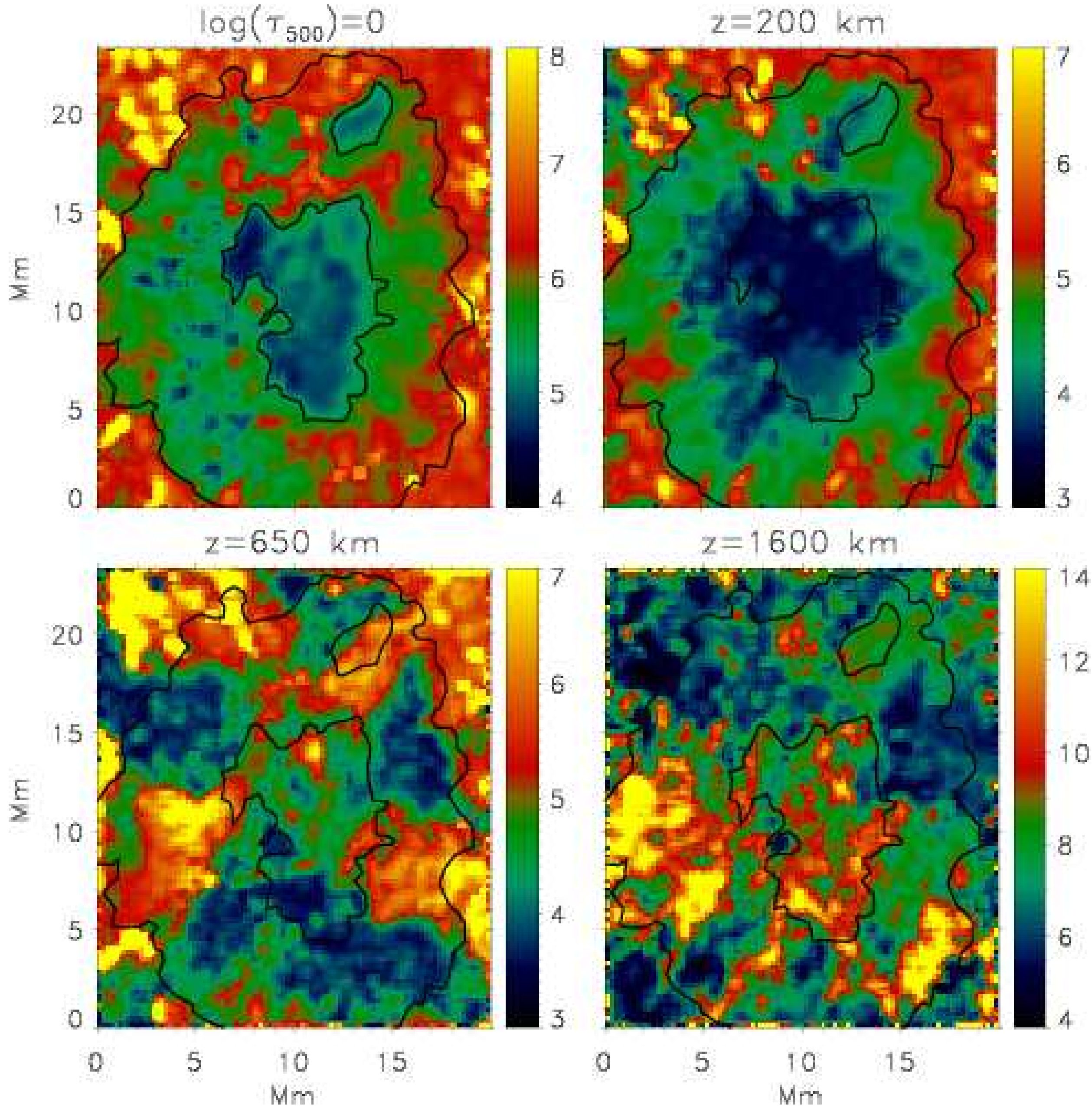

Fig. 3.— Temperature maps (in kK) at different heights in the atmosphere. Upper left: Temperatures at optical depth τ_{500}=1. Rest of the panels: Temperatures at geometrical heights z=200, 650 and 1600 km, respectively.

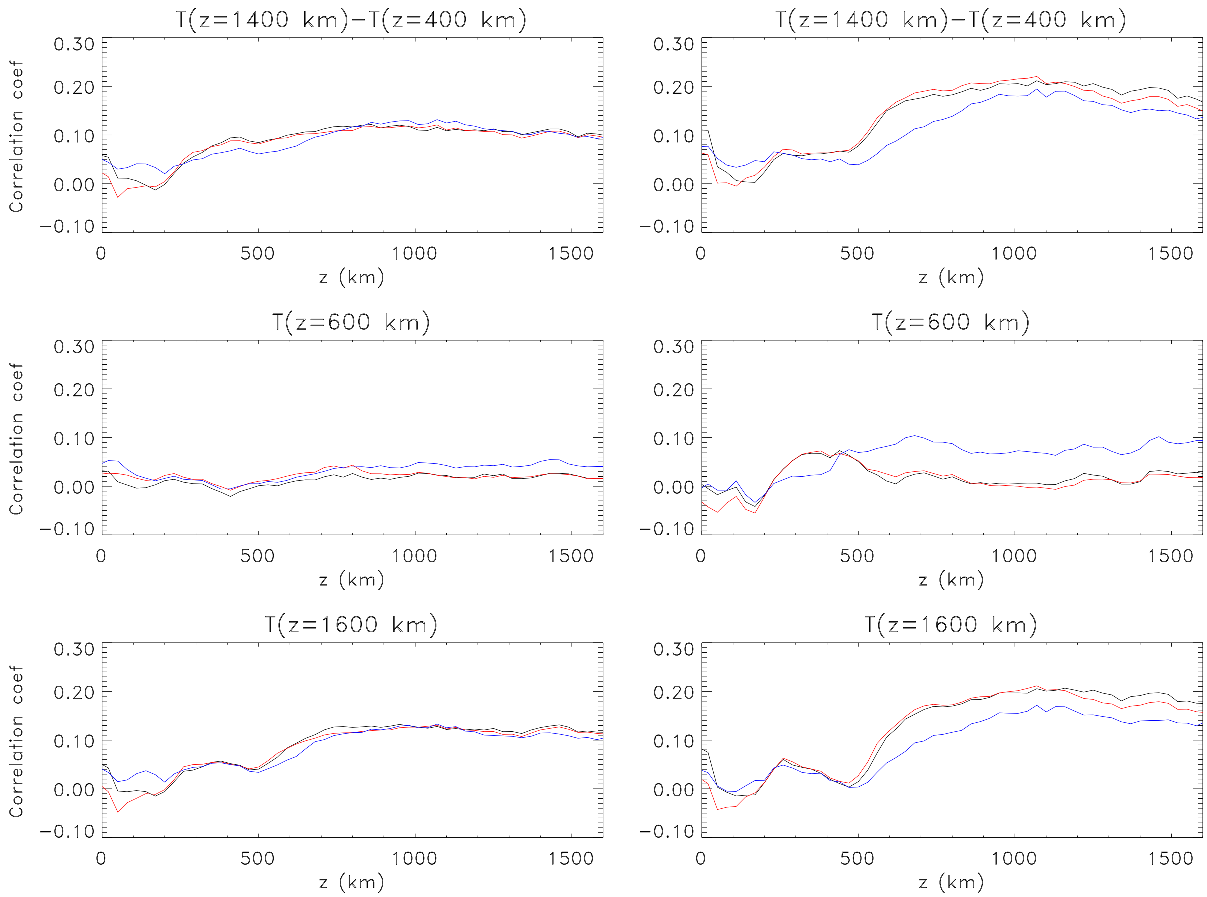

Fig. 4.— Pearson's correlation coefficient between the spatial distribution of temperatures at the geometrical height indicated by the label of each plot and the current densities at height z. The black line represents the modulus of the vector current density, whereas the red and blue lines represent the components perpendicular and parallel to the field, respectively. The upper panels refer to the temperature gradient between the upper photosphere and the chromosphere. Under strict radiative equilibrium conditions, this gradient should be slightly negative and the temperature would decrease monotonically with height. Therefore, the patches with positive temperature gradient are regions with important heating activity. The middle and lower panels depict the correlations between currents and temperatures at the lower and upper chromosphere, respectively. The left panels include the entire dataset, whereas the right panels are restricted to the sunspot penumbra only.